

Rock Permeability and Fluid Pressure at the KTB

Implications from Laboratory—and Drill Hole—Measurements

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Résumé — Perméabilité des roches et pression dans le KTB : enseignements tirés des mesures de laboratoire et des mesures en puits — La perméabilité des roches et la pression des fluides ont été étudiées à différentes échelles sur les deux forages du Programme continental de forage profond — *Continental Deep Drilling Program (KTB)*. Les essais de puits et les recherches d’inclusions de fluides impliquent l’existence d’une pression de fluide fonction de la salinité du fluide de formation. Les valeurs déduites des essais de puits dépassent largement les perméabilités matricielles, l’écart allant jusqu’à trois ordres de grandeur. De plus, l’évolution de la perméabilité mesurée sur échantillon en fonction de la pression et celle déterminée *in situ* diffèrent largement. Ces observations renforcent la théorie bien connue des effets d’échelle. Cette conclusion est étayée par les observations des communications hydrauliques entre les deux forages. Ces effets d’échelle impliquent une hétérogénéité hydraulique prononcée dans le cadre du KTB. Ainsi, une modélisation stochastique sur réseau avec des paramètres dérivés des mesures en forage et la prise en compte des perméabilités observées a été réalisée. En supposant que des forces motrices existent, le transport de fluide se fait essentiellement par des chemins connectés discrètement, caractérisés par une largeur, une longueur, et une orientation de fracture.

Mots-clés : perméabilité des roches, pression des fluides, forage profond, largeur de fracture, longueur de fracture, orientation de fracture, KTB, modélisation stochastique.

Abstract — Rock Permeability and Fluid Pressure at the KTB. Implications from laboratory—and drill hole—measurements — Rock permeability and the fluid pressure were investigated at different scales at the two drill holes of the Continental Deep Drilling Program (KTB). Drill hole tests and fluid inclusion investigations both implicate the existence of hydrostatic fluid pressure *in situ* with respect to salinity of the formation fluid. Matrix permeability and *in situ* values from hydraulic tests differ up to three decades with higher values *in situ*. Further on, the pressure dependence of core permeability and *in situ* determined values differ significantly. All these observed effects support the well known theory of scale variance. This conclusion is supported by observations of hydraulic communications between both drill holes. These scale effects implicate a pronounced hydraulic heterogeneity of the KTB surroundings. Therefore, stochastic network modelling with parameters derived from structural borehole measurements and under the consideration of the observed permeabilities were performed. Under the presumption of existing driving forces fluid transport takes place dominantly on discrete connected pathways characterised by fracture width, fracture length and fracture orientation and is subordinate in the rock matrix.

Keywords: rock permeability, fluid pressure, deep drill hole, fracture width, fracture length, fracture orientation, KTB, stochastic network modelling.

INTRODUCTION

Knowledge of rock properties controlling the fluid movement are a basic prerequisite to understand the dynamical processes, temperature and stress regime in the upper crust. The hydraulic flow can be quantitatively described by rock permeability, assuming rocks with homogeneous, interconnected pore space and a representative elementary volume (REV). In crystalline rock, this definition is somewhat problematic; the fluid pathways are due to fracture systems at various scales, which give different results depending on the scale of investigation, i.e. the quantity is not scale-invariant (Brace, 1984; Clauser, 1992). Therefore, the investigation of permeability is one of the main objectives for the two drill holes at the Continental Deep Drilling Program (KTB) (Huenges *et al.*, 1997). The paper compiles the state of the art understanding the hydraulic behaviour in the surroundings of the KTB.

Considering permeability on a macroscopic scale representing an integral value for a region, this quantity depends on relatively large, irregular fracture systems. This permeability can not be verified by core measurements, but can be estimated by hydraulic experiments in drill holes, yielding integral values but limited to a few depth intervals due to the high costs. On the microscopic scale permeability can be determined by core measurements with confining pressure to simulate the in situ conditions. These results yield values for matrix permeability and represent a rock composition with microfractures similar to the macroscopic fractures but with different frequency of the geometrical structures of the fractures and geological origin.

Besides direct measurements of permeability several methods exist to determine permeability indirectly. One method is modelling of hydraulic flow in fracture networks, but the transfer of the complex structure of natural rocks into equivalent models is a quite complicated problem and depends on the quality of the data base for construction of the fracture networks. Another technique to estimate permeability uses the micro seismic activity induced during hydraulic experiments (Shapiro, Huenges and Borm, 1997). The aim of this paper is a combined consideration of permeability measurements and pressure dependence on different scales of investigation with given references for the detailed descriptions of the applied methods.

1 HYDRAULIC TESTS

To study the hydraulic situation in the two drill holes of the KTB, several hydraulic tests were carried out (Huenges *et al.*, 1997). These can be divided into different types, depending on the shut-in volume and the direction of flow (injection or inflow). The quality of the tests is a question of the well bore storage, a measure of the shut-in volume multiplied by the

mud compressibility, the time of investigation and the pressure stimulation. Optimum results can be expected with minimum well bore storage, increasing monitoring time and increasing pressure. Therefore, the most reliable data were obtained by build up pressure tests with short-packed drill hole sections. Figure 1 shows the results of the build up tests in the pilot well (Vorbohrung) up to 4000 m and in the deep well (Hauptbohrung) in two sections at 6010 m and at final depth of 9101 m. The values of these tests with small shut-in volume vary between $5 \cdot 10^{-20} \text{ m}^2$ and $3 \cdot 10^{-16} \text{ m}^2$ and document the scattering of permeability on the meter scale of investigation.

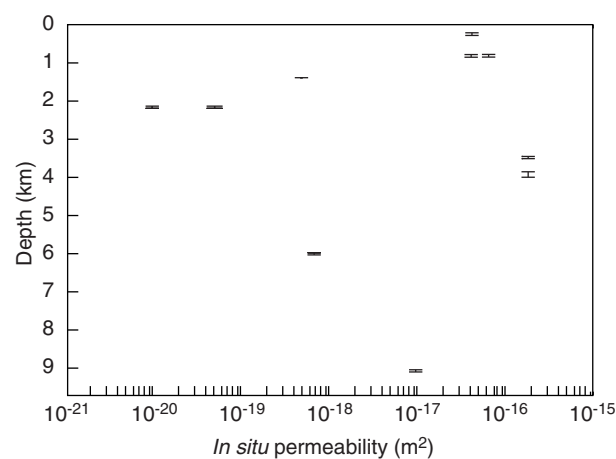


Figure 1

Permeability in KTB Vorbohrung and Hauptbohrung from hydraulic tests: (solid vertical lines) build up tests in Vorbohrung and in the Hauptbohrung. The vertical lines are limited by horizontal lines that give the borders of the packed or open borehole sections during each test.

2 FLUID INJECTION INDUCED SEISMIC EMISSION

During a hydraulic fracturing experiment at bottom hole of the KTB deep drill hole (Engeser, 1996), the injected fluid induced approximately 400 microearthquakes (Zoback and Harjes, 1997). These data were used by Shapiro *et al.* (1997) to calculate permeability from hydraulic diffusivity, which they estimated from the spatio-temporal distribution of all located events (Fig. 2). With this method hydraulic diffusivity values were estimated in the order of $0.5 \text{ m}^2 \text{ s}^{-1}$ with respect to the increased fluid pressure conditions during the experiment.

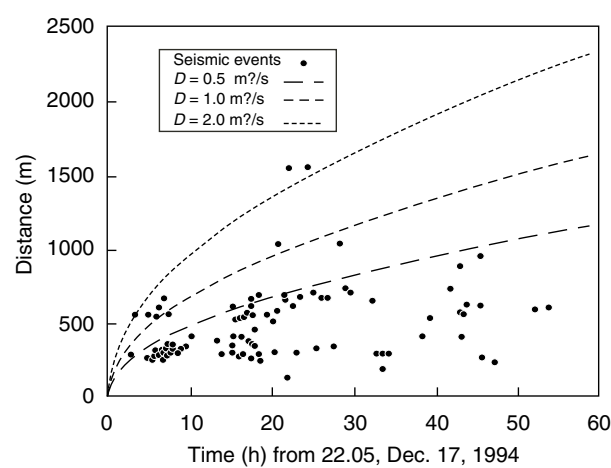


Figure 2

Distances of the seismic events from the center of the injection interval versus their time of occurrence (Shapiro *et al.*, 1997). Lines represent calculated distance-time curves of constant diffusivity.

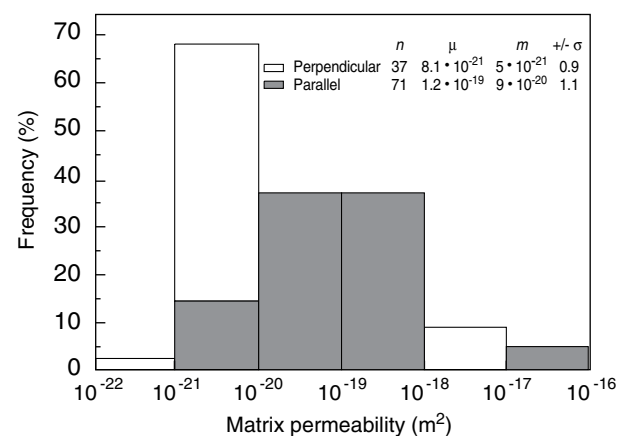


Figure 3

Permeability of cores recovered from up to 4 km depth of KTB Vorbohrung and 7.4 km depth of Hauptbohrung, measured parallel and perpendicular to the foliation of the rock, composed of gneisses and amphibolites. Here n is the number of data, μ is the geometric mean, m is the median, and σ is the logarithm of standard deviation (Huenges *et al.*, 1997).

3 LABORATORY MEASUREMENTS

Core permeability was measured at simulated *in situ* conditions on core samples with a specimen size of a few centimetres (Berckhemer *et al.*, 1997). These measurements show a strong anisotropy parallel and perpendicular to the foliation axes (Fig. 3). The mean values of core permeability are $1.4 \cdot 10^{-19} \text{ m}^2$ parallel and $7.6 \cdot 10^{-21} \text{ m}^2$ perpendicular to the foliation axes suggesting a log-normal distribution for the data. These results represent the matrix permeability of the fractured rocks. They represent a permeability on a microscopic scale, which differs up to three orders in magnitude to the results from hydraulic tests and therefore have no REV.

4 PRESSURE DEPENDENCE OF PERMEABILITY

The pressure dependence of the core samples were measured in an autoclave under uniform pressure up to 240 MPa (Millich *et al.*, 1998). For permeabilities on the drill hole scale, pressure dependence was derived from injection tests (Huenges *et al.*, 1997). Figure 4 documents the difference of three orders in pressure dependence between the core measurements and the drill hole tests.

The more pronounced *in situ* pressure dependency indicates a “softer” mechanical behavior of the fracture systems in contrast to the more compact microscopic pores in laboratory samples. The mechanical behavior of the rock mass depends on the number and the width of the fractures (see Kessels and Kück, 1995). Higher values of both and a “softer” behavior of the rock mass is therefore more likely *in situ* than in laboratory samples.

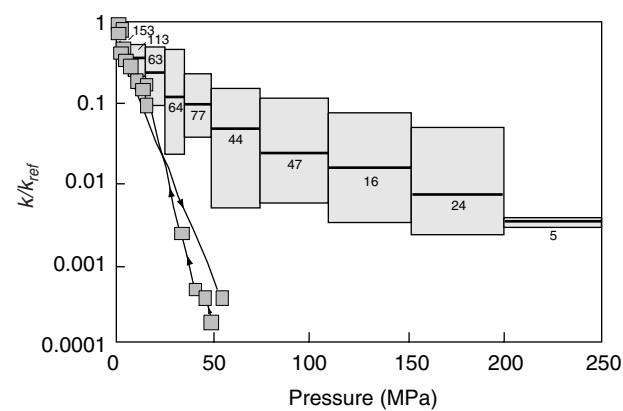


Figure 4

Variation of permeability of rocks with effective pressure p . Permeability is normalized to permeability at zero-effective pressure k_{ref} using the measured value at lowest pressure and some extrapolation. The variation of the core data within a pressure interval is illustrated by gray shaded blocks showing the mean values (middle lines), standard deviation and the number of data available in the different pressure ranges within the blocks. Pressure-dependent borehole data—yielded by tests with several injection pressure steps into a 20 m open hole section in KTB at 6 km depth—are plotted as squares connected by a solid line (Millich *et al.*, 1998).

5 FLUID LEVEL STUDIES

The observation of fluid level fluctuations lead to estimations of *in situ* petrohydraulic parameters like tidal sensitivity, static confined barometric efficiency and the Skempton ratio

(Schulze, Kümpel and Huenges, 1999). The fluid level in the pilot well of the KTB shows a tidal signal of 0.13 m. The static confined barometric efficiency was obtained by measuring the air pressure and fluid level changes simultaneously and amounts to approximately 0.60-0.65. The Skempton ratio (Skempton, 1954; Rice and Cleary, 1976) is a measure of the change in pore pressure to confining pressure for undrained conditions and was estimated by Schulze *et al.* (1999) to 0.40 to 0.45 in consistence with the areal strain sensitivity. In the deep drill hole the fluid level does not present any tidal or barometric signals so far, but a monotonous lowering of the fluid level.

6 FORMATION PRESSURE

From surface to bottom hole an average formation pressure gradient was determined to 11.5 MPa/km (Fig. 5) (Huenges *et al.*, 1997). Considering a water column of fresh water at related temperatures and pressures, the gradient is approximately 9.5 MPa/km. This discrepancy can be explained by the salinity of the mud; an increase of salinity was observed at a transition zone below 2000 m and below 6000 m due to a potentially corresponding fracture system between 4000 and 9000 m. Taking this into account, the increase of formation pressure can be explained by density increase due to salinity increase and implies a hydrostatic formation pressure.

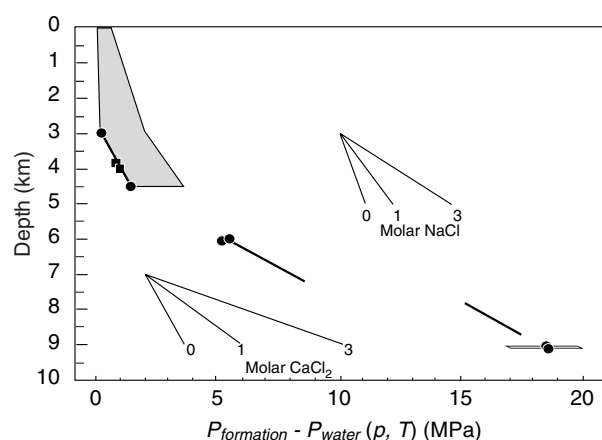


Figure 5

Formation pressure as a function of depth of the KTB location reduced by the pressure of a fresh water column. The density of the water was calculated with respect to pressure and temperature. Solid squares show results from fluid level observations in the Vorbohrung, solid circles show results from build up tests in the Hauptbohrung, and solid lines show data from large-volume injection tests of the open hole sections. Hatcheries mark the field of uncertainty. The theoretical gradients due to differently composed NaCl and CaCl_2 mud columns are shown (Huenges *et al.*, 1997).

7 FLUID INCLUSIONS

Fluid inclusions in minerals reflect the fluid composition and the *in situ* pressure as a function of depth. Grawinkel and Stöckhert (1997) studied about 250 inclusions from 9 samples from the KTB-drill holes up to 9 km depth. Their microthermometric results show NaCl dominated aqueous fluid inclusions with low salinity (< 4% NaCl equiv.) up to 4000 m and higher salinity inclusions at greater depth (up to 24% NaCl equiv.), which are dominated by CaCl_2 . The analysis of isochores (temperature-pressure line at constant density) indicate a hydrostatic pore fluid pressure up to approximately 9000 m.

8 MODELLING

Deterministic as well as stochastic fracture networks were modelled at the two drill hole of the KTB to simulate the hydraulic flow (Zimmermann, Körner and Burkhardt, 1999) using the geometry of the fractures such as fracture locations and orientations, which were determined by structural drill hole measurements creating an image of the drill hole wall. Potentially open fractures were selected according to the stress field. Only fractures with the dip direction (azimuth) of the fracture plane perpendicular to the maximum horizontal stress field were assumed to be open.

The stress regime in the vicinity of the KTB were investigated by Brudy *et al.* (1997). They estimated the upper and lower bound of the maximum and minimum horizontal stress and showed that the maximum horizontal stress is higher than the vertical stress from the formation, indicating that the state of stress is a strike-slip faulting (Zoback and Harjes, 1997). From this point of view, this is a presumption for an overthrusting of the Bohemian Massif on the South German basin and in this brittle ductile zone the shear horizons occur as a number of connected fractures. Therefore, the stress situation is responsible for a hydraulically active fracture system.

Length scales for fracture width and extensions were stochastically varied and calibrated by a hydraulic communication experiment between the two drill holes (draw down test from 3000 to 6000 m in the main drill hole) (Kessels and Kück, 1995). They estimated the permeability between the drill holes from transmissibility and inflow horizon to approximately $2.9 \cdot 10^{-16} \text{ m}^2$. Taking this into account, a 2D stochastic fracture network was generated, which led to the estimation of the mean fracture width to 25 μm assuming an exponential distribution function.

At approximately 7000 m the Franconian lineament, a prominent fault zone, strikes the KTB main drill hole. At this depth section, three different stochastic networks with fracture lengths of 30 m, 50 m and 100 m respectively were constructed (Fig. 6), which are equivalent according to connectivity and linear fracture frequency, which was determined visually by the Formation Microscanner (FMS) logging tool. The

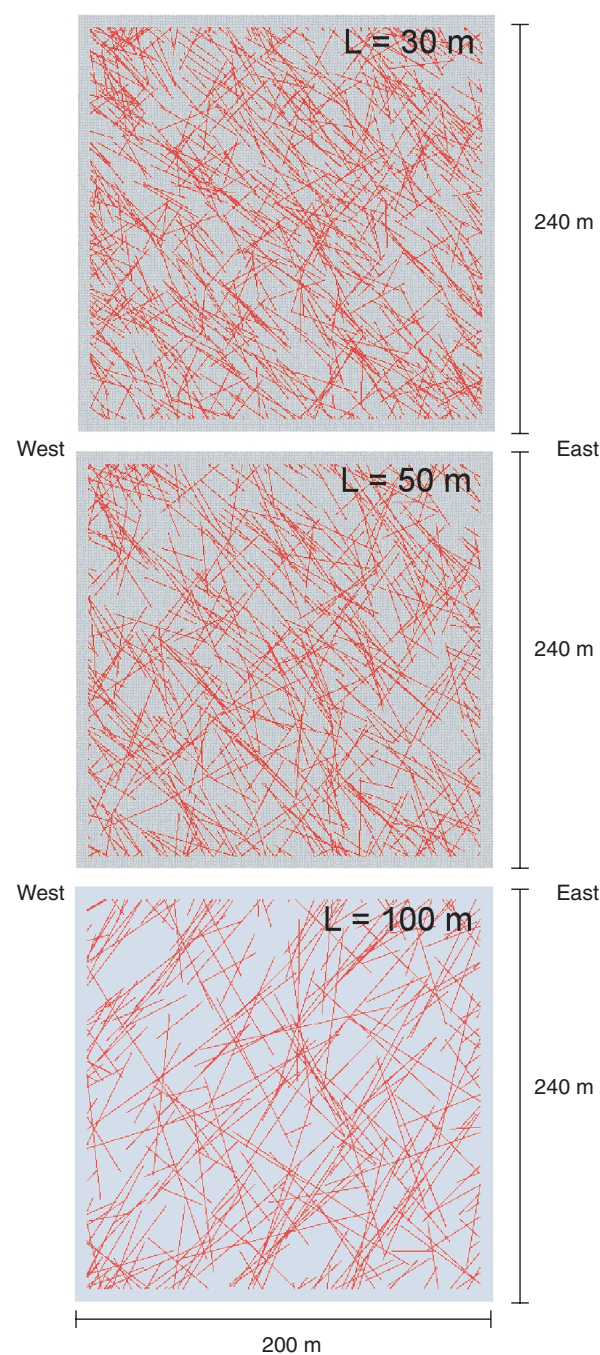


Figure 6
Stochastic fracture networks used for modelling with geometrical data from the depth section of the Franconian lineament (6900 to 7140 m KTB-HB, projection in W-E-direction). The orientation of the fractures is perpendicular to the maximum horizontal stress (Brudy *et al.*, 1997) and is divided into two sets with a difference in azimuth of 180°. The number of fractures per area were calculated from the detected fractures from FMS measurements; the fracture length was set to 30 m, 50 m and 100 m. Variation of the mean fracture width leads to various permeability estimations (Table 1) (Zimmermann *et al.*, 1999).

networks are hydraulically conductive. A further decrease of fracture lengths to less than approximately 10 m lead to a network beyond the percolation threshold, i.e. a non-conductive network, which does not fit to the *in situ* permeability data. Modelling the hydraulic flow of these three networks, permeability with respect to the direction of fluid flow is calculated in the range of 10^{-16} m^2 to 10^{-17} m^2 with a decrease in permeability with decreasing fracture length (Table 1).

TABLE 1
Comparison of permeabilities with exponential distribution of the fracture widths between the individual nodes of the fracture networks (k_h is calculated in horizontal and k_v in vertical direction)

	Mean permeability (10^{-18} m^2)	Standard deviation (10^{-18} m^2)
L100-model k_h	42.6	2.2
k_v	72.8	14.8
L 50-model k_h	27.8	3.0
k_v	37.3	4.3
L 30-model k_h	7.5	0.9
k_v	15.0	2.6

Fracture porosity was calculated from the flow volume of the fracture networks and is in the range of $10^{-3}\%$. Measurements of porosity from cores (Berckheimer *et al.*, 1997) and calculations from log measurements (Zimmermann, Burkhardt and Melchert, 1992; Pechnig *et al.*, 1997) lead to values in the range of 1%. These differences can be explained by a concept of double formation porosity, which is a combination of fracture and matrix porosity. The hydraulic flow is connected to fracture porosity, which serve as privileged pathways on the basis of the cubic law and therefore give the major contribution to the fluid transport, whereas the matrix serves as a storage of immovable formation fluids.

DISCUSSION AND CONCLUSION

Fundamental understanding of hydraulic parameters in crystalline rock like permeability, pressure dependence of permeability and the scale effect is still an open question. The two drill holes of the KTB offer a unique possibility to study the hydraulic behaviour of the upper crust.

At the current state of investigation we suggest a quasi hydrostatic formation pore pressure in the vicinity of the KTB and possibly this is valid for the upper crust in this area. This is supported by fluid inclusion measurements on the microscopic scale and from build up and injection tests on the macroscopic scale. The Skempton ratio of about 0.4 reflects the influence of the change in confining pressure to the change in fluid pressure and emphasises the important role of fluid pressure in transmitting stresses in the upper crust.

Matrix permeabilities are in the range of 10^{-19} m² with one decade standard deviation. Anisotropy of permeability is documented by measurements parallel and perpendicular to the foliation axes; permeability parallel to foliation is one decade higher. The differences between permeabilities from core measurements and hydraulic tests, which are up to three decades higher than the core measurements, are due to the well known scale effect. Pressure dependence of permeability between core measurements and in situ testing showed a clear difference for the pressure range of up to 50 MPa. As shown by the experiment at 6000 m depth permeability decreases by three orders of magnitude compared to one order for the core measurements. This agrees with the results from Rice (1992) from the San Andreas Fault. Nevertheless, it is a remarkable result for crystalline rock that in situ permeability does not decrease more than one order of magnitude up to the final depth of 9101 m to about $8 \cdot 10^{-18}$ m².

Further on, the hydraulic pathways seem to be of more than local extension; this was demonstrated by the hydraulic communication experiments between the two drill holes, which showed hydraulic conductive fracture networks between the bottom hole level of the pilot well and the main drill hole after reaching 6 km depth and at final depth of 9101 m. All these observed effects support the well known theory of scale variance.

To study the permeability structure, a broad spectrum of stochastic fracture networks were analysed. We favour a model with a reciprocal behaviour of permeability and porosity for the matrix and fractures. This can be described as a reversal model in contrast to a homogeneous isotropic medium. For this reason, true fluid velocities and the penetration of fluids in crystalline rock are substantially higher than for an equivalent homogeneous rock with a clear defined REV and the same formation permeability.

Therefore, the following lesson is given by the hydraulic KTB investigations:

Fluid transport, if driving forces exist, takes place on discrete connected pathways, which are kept open due to the particular stress field. The matrix is minor influenced by fluid transport. Fluid velocity in rocks with these discrete pathways is enhanced in comparison to homogeneous permeable rocks. This must be taken into consideration for any mass and heat transport modelling in such fractured rocks.

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